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Gunner Tracking Models for the BFVS-A3 Combat Vehicle Engineering Simulation

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Abstract

During fiscal year 2000, efforts continued to develop improved gunner tracking models for the U.S. Army Research Laboratory's Combat Vehicle Engineering Simulation (CVES). By the proper selection of input, CVES can be used to determine the fire control performance of either a conceptual or specific combat vehicle. CVES has been configured to model the M1A1 combat tank and the A3 version of the Bradley fighting vehicle system (BFVS-A3). CVES contains engineering models of the fire control system, chassis, suspension, and the gunner. This effort addresses the gunner models for the BFVS-A3 CVES.

Gunner models were developed via the interactive system identification algorithms from the MATRIXx® software package, along with measured gunner tracking error and gunner handle position data. Tracking error is the gunner's input and handle position is the gunner's output.

The resulting gunner tracking models are shown to be more accurate than the existing gunner tracking models used in CVES. These new models were installed in CVES, and it was then shown that the CVES is an accurate simulation for predicting the fire control performance of the BFVS-A3.

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GUNNER TRACKING MODELS FOR THE BFVS-A3 COMBAT VEHICLE ENGINEERING SIMULATION

1. Introduction

For fiscal year 2000, the Weapons and Materials Research Directorate of the U.S. Army Research Laboratory (ARL) continued to develop improved gunner tracking models for its Combat Vehicle Engineering Simulation (CVES). CVES is a generic code that, by the proper selection of input, can be used to determine the fire control performance of either a conceptual or specific combat vehicle. CVES contains detailed engineering models of the fire control system, chassis, suspension, and gunner. The CVES user configures a combat vehicle by selecting an ammunition type, fire control configuration, type of turret and gun drives, and gunner. CVES uses a six-degree-of-freedom model to determine the motion of the chassis. Additional input to the CVES includes target path motion, combat vehicle path motion, and the terrain over which the combat vehicle travels. CVES has been configured to model the M1A1 combat tank and the A3 version of the Bradley fighting vehicle system (BFVS-A3).

Several years ago, the output of the M1A1-configured CVES was compared to actual data. The results of this comparison showed that the simulation did a very good job of duplicating the lead angles but only a fair job of replicating the tracking errors (Corcoran & Perkins 1997). Thus, there was a need to develop better gunner tracking models for the M1A1 CVES. These improved gunner models for the M1A1 CVES were built during fiscal years 1998 and 1999 (Corcoran 1999). The effort proved to be successful so that a similar effort was conducted during fiscal year 2000 to develop improved gunner models for the BFVS-A3 configured CVES.

Like the M1A1 effort, the BFVS-A3 gunner tracking models were developed with the interactive system identification algorithms from the MATRIXx® software package, along with measured gunner tracking error and handle position data (Integrated Systems 1995). The measured data were from a BFVS-A3 tracking test conducted by the Aberdeen Test Center (ATC) during 1999. These newly developed models were shown to be more accurate than the existing CVES gunner models. They were then installed in the CVES, and the simulation output of gunner tracking error and gun lead angle was compared with actual data. This comparison showed that the CVES could be configured to be an accurate simulation for predicting the fire control performance of the BFVS-A3.

The purpose of this report is to describe the development of the gunner tracking models for the BFVS-A3 and to show the comparison of the BFVS-A3 CVES output with actual data.

2. Procedures

As mentioned, the measured gunner input and output data were obtained from a tracking test conducted in 1999 to determine the fire control performance of a stationary BFVS-A3 engaging an evasive target. This testing was conducted in the ATC's moving target simulator (MTS). The MTS is an air-supported hemispherical structure that is 60 meters in diameter. The system undergoing test is placed inside the MTS and is instrumented appropriately. A laser spot projected onto the wall of the MTS represents the target. Target motion at a given range is simulated by moving the laser spot with a computer-generated signal that is proportional to the target's angular displacement referenced to the system being tested. The gunner tracks the spot as though it were a target; the simulated range to the target is manually entered by the gunner in the ballistic computer (since the laser range finder cannot be used to measure range in the test setup), and the tank's fire control system aims the gun. Time histories of various engineering quantities are recorded for each trial. A big advantage of conducting tests in the MTS is the repeatability of target motion.

Testing was conducted against two simulated evasive ground targets: the Army Materiel Systems Analysis Activity (AMSAA) and the antitank missile test (ATMT) target paths. Both target paths are part of the target path set used by ATC when it conducts a gunner tracking or fire control test. The AMSAA path is an analytical path, whereas the ATMT target represents the actual motion of a tactical vehicle measured during a field test of the same name. Neither of these paths has an elevation component. Therefore, to provide the gunner with an elevation tracking task, the BFVS-A3 was canted 3.55 degrees with the right side up.

The lateral motion of the AMSAA and ATMT targets referenced to the canted BFVS-A3 is shown in Figures 1 and 2, respectively. One can obtain the vertical motion of these targets by multiplying the amplitudes shown in Figures 1 and 2 by the tangent of the cant angle (tan 3.55 degrees = 0.062). The vertical motion is correlated to a coordinate system attached to the canted BFVS-A3.

These targets were maneuvering at simulated ranges of 1.2 and 1.6 kilometers. The gunners simulated firing armor-piercing discarding sabot rounds with tracer (APDS-T) and high explosive incendiary rounds with tracer (HEI-T) at the targets.

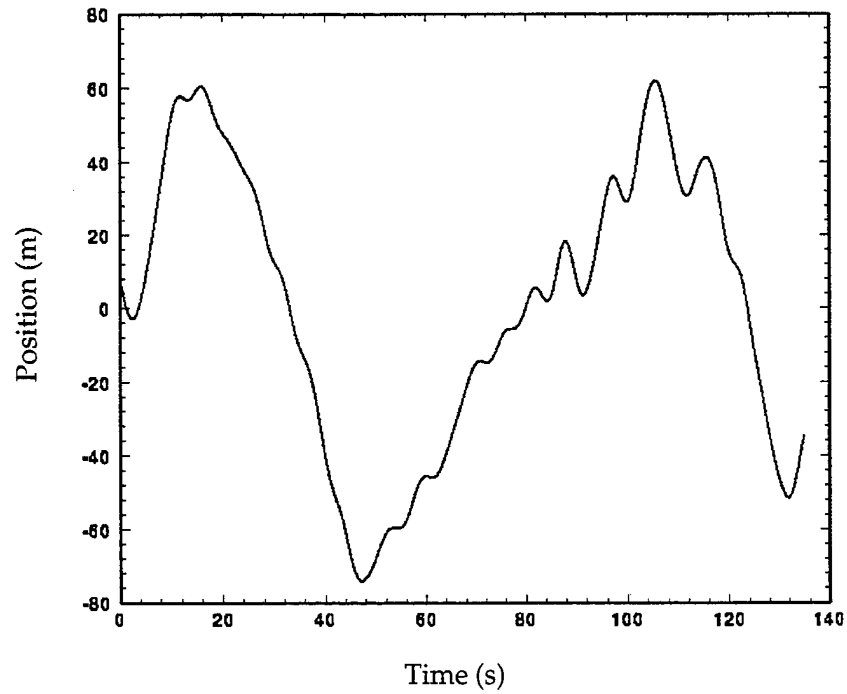

Figure 1. AMSAA Target - Lateral Motion.

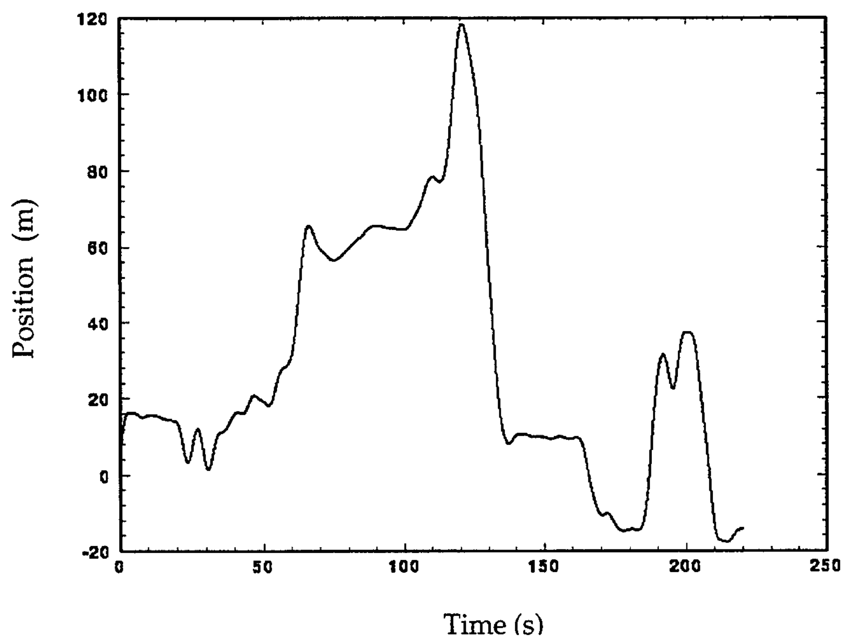

Figure 2. ATMT Target - Lateral Motion.

Typically, four manual tracking trials were conducted for each test condition. To obtain representative azimuth and elevation gunner input and output for each of the conditions tested, tracking errors from like trials were averaged together as a function of time, as were the handle position signals. These average time histories were then used as the input to the MATRIXx® Xmath interactive system identification algorithms, and an azimuth and elevation gunner tracking

model was developed for each of the test conditions. Typical averaged time histories of the input and output when the gunner tracks each of the target paths are shown in Figures 3 through 6, respectively.

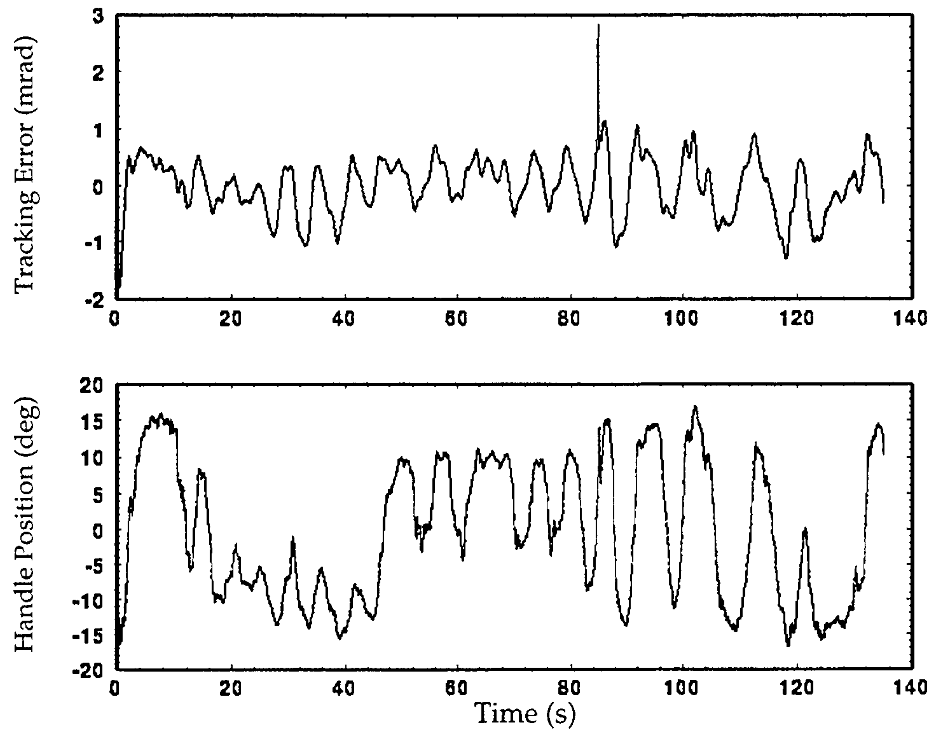

Figure 3. Gunner Azimuth Input and Output, AMSAA Path at 1.6 km.

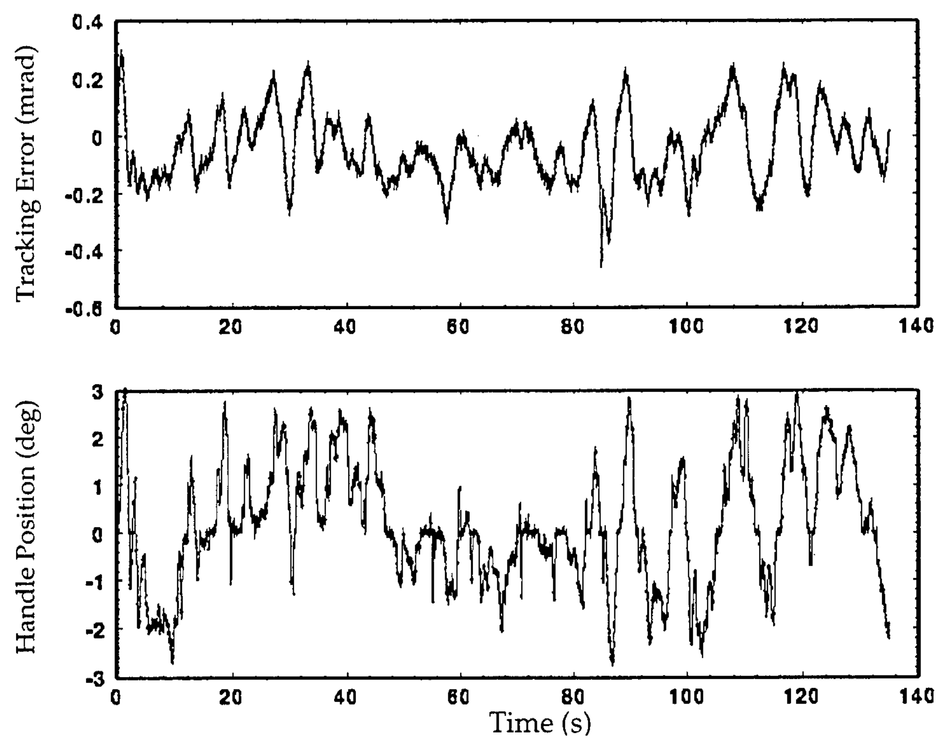

Figure 4. Gunner Elevation Input and Output, AMSAA Path at 1.6 km.

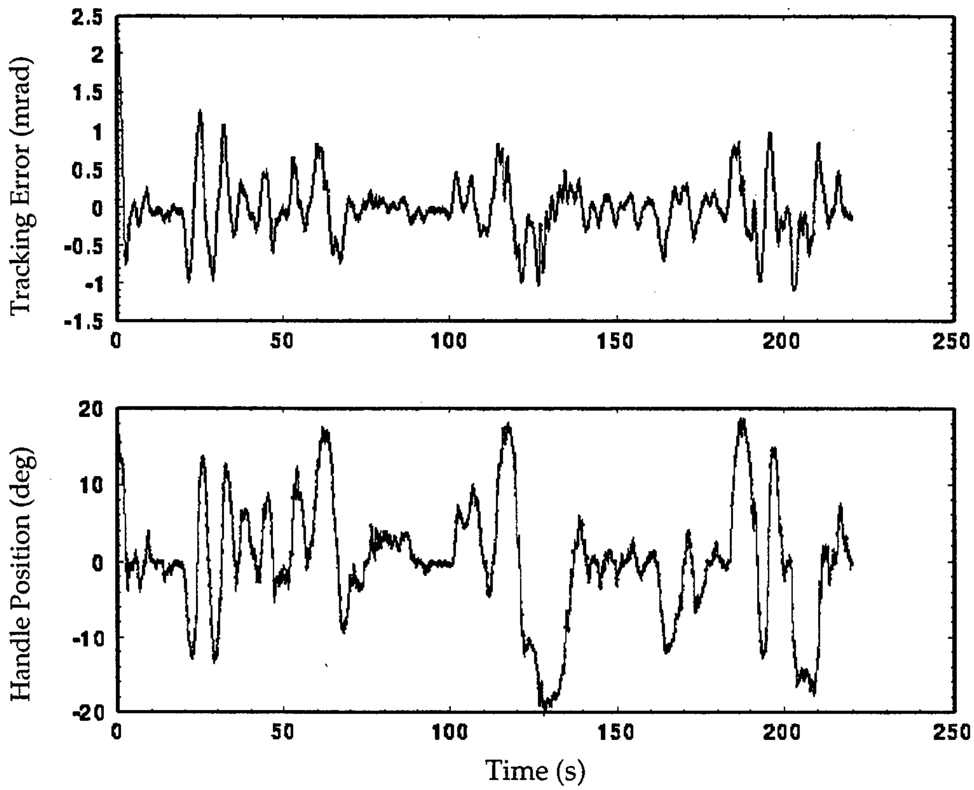

Figure 5. Gunner Azimuth Input and Output, ATMT Path at 1.2 km.

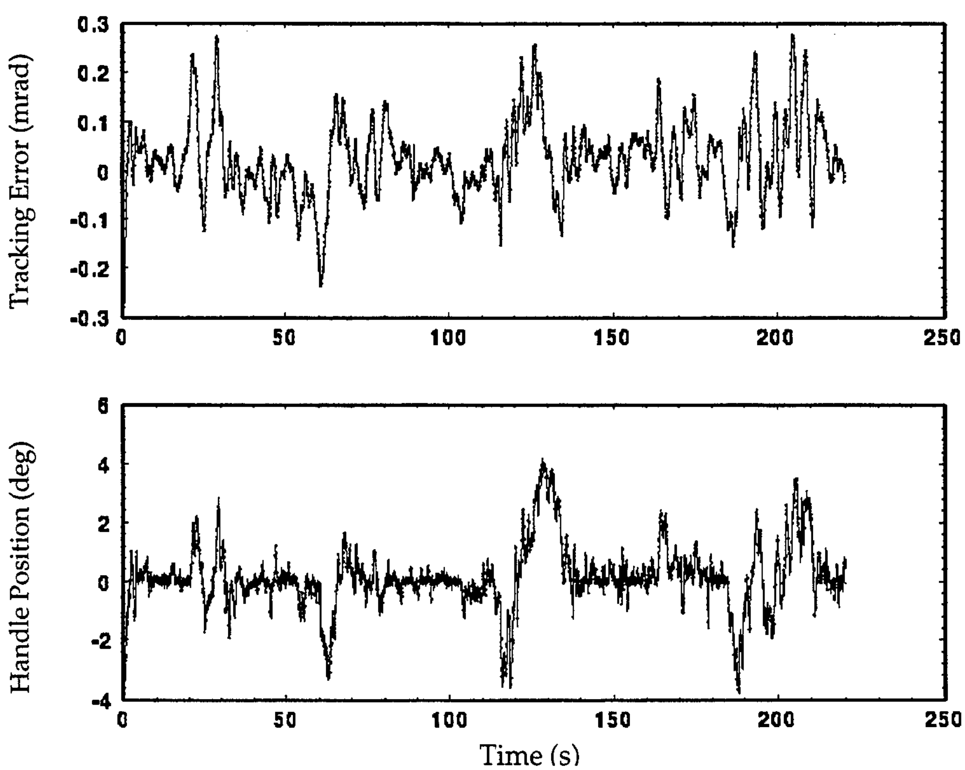

Figure 6. Gunner Elevation Input and Output, ATMT Path at 1.2 km.

The first step in the gunner model development process was to remove the mean from the tracking error and handle position signals. The resulting time histories were then split so that the first half of the time history data was used to identify the model and the second half was used for model validation. The next step was to select an identification algorithm. There are a number of MATRIXx® algorithms to choose from, but the algorithm based on least squares techniques was found to be suitable for use with these data. For details about the least squares identification algorithms, the reader is referred to the MATRIXx® manuals (Integrated Systems 1996).

The output of the least squares identification algorithm was a series of first through fifteenth order single input-single output linear time-invariant models for each one of the conditions tested.

From the previous gunner modeling experience with the M1A1, the fundamental form of the gunner model was found to be mostly a function of the target path tracked. Thus, it was decided that an azimuth and elevation gunner model would be installed in the CVES for each target path tracked, provided that these new models were more accurate than the existing CVES gunner models. The problem then became how to best select the appropriate gunner models from each set of 15 models identified.

To solve this problem, we computed the accuracy of each identified model by employing the so-called error norm. The error norm provides a measure of how well the model output agrees with the actual measured output. It is defined in the MATRIXx® literature as the standard deviation of the model error divided by the standard deviation of the actual measured gunner output. The model error is the difference between the model output and the actual gunner output. Therefore, a model with a lower error norm would be a more accurate model. For each target path, the error norms for those models of the same order were averaged together. We then selected the model order for each target path by considering the average error norms or accuracies.

The error norms associated with the AMSAA target path showed that the first order azimuth and elevation gunner models were slightly less accurate than the higher order models. However, the error norms associated with the ATMT target path showed that the first order azimuth and elevation gunner models were slightly more accurate than the higher order models. Therefore, based on their overall accuracy and simplicity, first order models were selected to be representative of the BFVS-A3 gunners tracking the AMSAA and ATMT target paths.

The coefficients of the first order models then had to be determined. In the frequency domain, this meant that the lag frequency, lead frequency, and the gain of each model or transfer function had to be determined. The averaging

process was again used to determine these coefficients for the four fundamental transfer functions. For a given target path, the average of the first order model lag frequencies was computed, as was the average of the lead frequencies. These average frequencies became the lag and lead frequencies of the first order gunner model associated with a given target path.

In addition to determining the lag and lead frequencies of the transfer function, it was also necessary to determine the steady state gain of the transfer function. This is the ratio between the handle position and the tracking error at zero frequency. The handle's output is a signal that provides an estimate of the target's angular rate, provided that the gunner is doing a reasonable job of tracking the target. Therefore, if the tracking error amplitudes remain constant over range for a given target path, the steady state gain will decrease as the target range increases (the target's angular rate is decreasing). For a given target path, the gains of the first order gunner models at a given range were averaged together, and a linear fit was applied to these averaged gains to estimate the steady state gain of the gunner model as a function of range.

The form of the resulting gunner model when each target path is tracked was therefore a first order model with a gain that varied as a function of range to the target.

The accuracy of these newly developed gunner models was then compared to the accuracy of the existing gunner models that are used in the CVES. There would be no reason to use the new models in the CVES unless they were more accurate than the existing models. CVES has one gunner model for the azimuth axis and one gunner model for the elevation axis, and these models are used, regardless of the combat vehicle-to-target scenario. We evaluated the newly developed and existing models by comparing their error norms and their output time histories. The results of this comparison showed that the newly developed models were much more accurate than the existing CVES models.

These new models were then installed in CVES. CVES was driven by the two target paths considered in this study, and the simulation tracking errors and lead angles were compared with measured data. The results of this exercise showed that the CVES with the newly developed gunner models is an accurate simulation for predicting the fire control performance of the BFVS-A3.

3. Results

3.1 Gunner Model Selection

The error norms or accuracies of the azimuth and elevation gunner models of Orders 1 through 4 identified with the MATRIXx® least squares algorithm when

the AMSAA target path was tracked are shown in Table 1. (Since there was no appreciable change in accuracy for model orders greater than 4, they are not shown.)

Table 1. Error Norms for Gunner Models Identified Via Least Squares - AMSAA Target Path

		Model Order							
Range		Azimuth				Elevation			
(Km)	Round	1	2	3	4	1	2	3	4
1.2	APDS	33.3	29.8	29.1	29.2	49.8	40.2	42.4	44.2
1.2	HEI	36.4	33.6	33.0	32.7	56.5	39.3	42.9	43.6
1.6	APDS	33.7	29.6	29.1	29.6	60.5	58.8	60.2	60.2
1.6	HEI	36.7	33.0	31.4	32.1	72.0	62.6	63.1	63.6
Average		**35.0**	**31.5**	**30.7**	**30.9**	**59.7**	**50.2**	**52.2**	**52.9**

(Table entries are in percent.)

Similarly, the error norms of the azimuth and elevation gunner models when the ATMT target path was tracked are shown in Table 2.

Table 2. Error Norms for Gunner Models Identified Via Least Squares - ATMT Target Path

		Model Order							
Range		Azimuth				Elevation			
(Km)	Round	1	2	3	4	1	2	3	4
1.2	APDS	36.0	38.7	40.8	39.5	65.4	74.0	72.6	72.4
1.2	HEI	25.2	35.1	37.9	34.8	66.5	76.5	75.7	75.8
1.6	APDS	27.5	29.1	32.0	29.3	45.0	58.6	57.7	57.5
1.6	HEI	23.9	29.0	29.6	26.9	70.4	77.5	77.7	77.8
Average		**28.2**	**33.0**	**35.1**	**32.6**	**61.8**	**71.7**	**70.9**	**70.9**

(Table entries are in percent.)

Tables 1 and 2 show that the azimuth models are more accurate than the elevation models. The average error norms of the azimuth models range from 28.2% to 35.1%, whereas the average error norms of the elevation models range from 50.2% to 71.7%.

From Table 1, it is seen that on the average, the error norms for those gunner models identified from the AMSAA target path tracking and handle data tend to

decrease as the model order increases from the first through fourth order. This means that the output from the higher order models is showing somewhat better agreement with measured data. On the other hand, it is seen from Table 2 that the error norms for those models identified from the ATMT target path data tend to increase as the model order is increasing. This means that the output from the first order models is showing somewhat better agreement with measured data.

Based on the average error norm results presented in Tables 1 and 2, which show that overall the accuracies of the first order models are about as good as the higher order models, first order models were selected as being representative of BFVS-A3 gunners tracking a maneuvering target.

First order models are simple since they consist of a gain, one lag frequency, and one lead frequency. The form of this model, or transfer function *G(s)* as a function of frequency, which relates the handle position to the tracking error, is shown in the following equation:

$$G(s) = K\frac{(\tau_{lead}s+1)}{(\tau_{lag}s+1)}$$

In this equation, "s" is the LaPlace transform operator, K is the steady state gain, τ_{lead} is the lead time constant, and τ_{lag} is the lag time constant. The lead and lag frequencies, ω_{lead} and ω_{lag}, expressed in radians (rads) per second, are the reciprocals of the lead and lag time constants.

3.2. Lag and Lead Frequencies and Gain Selection

Tables 3 and 4 show the lag and lead frequencies, along with the gains for each first order model, that were identified for each test condition.

Table 3. Gunner Model Parameters - AMSAA Target Path

Range (Km)	Round	Azimuth ω_{Lead}	Azimuth ω_{Lag}	Azimuth K	Elevation ω_{Lead}	Elevation ω_{Lag}	Elevation K
1.2	APDS	1.98	0.19	59.26	4.01	0.30	36.50
1.2	HEI	1.51	0.18	55.94	3.48	0.29	31.28
1.6	APDS	1.43	0.21	46.76	3.46	0.45	20.73
1.6	HEI	1.77	0.25	49.68	3.84	0.47	22.38
Average		**1.67**	**0.21**	**N/A**	**3.70**	**0.38**	**N/A**
Standard Deviation		**0.25**	**0.03**	**N/A**	**0.27**	**0.10**	**N/A**

Table 4. Gunner Model Parameters - ATMT Target Path

Range (Km)	Round	Azimuth ω_{Lead}	ω_{Lag}	K	Elevation ω_{Lead}	ω_{Lag}	K
1.2	APDS	1.33	0.23	42.91	10.72	0.85	16.02
1.2	HEI	1.25	0.14	64.86	3.36	0.48	17.63
1.6	APDS	1.63	0.28	42.82	5.20	0.59	14.37
1.6	HEI	1.79	0.25	50.44	8.23	0.66	11.47
Average		**1.50**	**0.23**	**N/A**	**6.88**	**0.65**	**N/A**
Standard Deviation		**0.25**	**0.06**	**N/A**	**3.25**	**0.16**	**N/A**

In Table 3, it is seen that average azimuth and elevation lead frequencies are larger than the average lag frequencies. It also is seen from the azimuth and elevation standard deviations that the lag and lead frequencies are rather consistent for the models developed with the AMSAA target path tracking error and handle position data. A cursory power spectral density analysis showed that most of the tracking error occurs at frequencies that are below 1.25 rad/s. Therefore, the lag terms, being less than 1.25 rad/s, will have an effect on both the gain and phase response between the input and output. The lead terms, being greater than the tracking error frequencies, will affect primarily the phase shift between the input and output, especially for those tracking error frequencies that are greater than 0.17 rad/s in azimuth and 0.37 rad/s in elevation. It is also seen that the steady state gains in both azimuth and elevation are decreasing as the target range is increasing.

The results shown in Table 4 when the ATMT target path was tracked are similar to those shown in Table 3. It is not readily apparent that the azimuth steady state gains are decreasing as the target range is increasing. However, if the azimuth gains at the same range are averaged together, the decreasing gain trend can be seen. Also, the elevation lead frequency is showing a large variation. This large variation may be the result of noisier elevation data.

Now that the average lag and lead frequencies for the first order models associated with each of the target paths have been determined, the gain function for each model was determined. Since there were only two ranges to work with, a linear fit was applied to the identified gains. The equations for the gain of each model, expressed as a function of target range in kilometers, are shown in Table 5. These gain functions are for target ranges of 1.2 to 1.6 kilometers.

Table 5. Gunner Model Gain Functions

Model	Gain Function
AMSAA Azimuth	$K = -23.45r + 85.74$
AMSAA Elevation	$K = -30.84r + 70.90$
ATMT Azimuth	$K = -18.14r + 75.65$
ATMT Elevation	$K = -9.76r + 28.54$

3.3 A Comparison of Gunner Tracking Models

The error norms or accuracies for the newly developed least squares gunner models and the existing CVES azimuth and elevation gunner models when the AMSAA and ATMT target paths were tracked are shown in Tables 6 and 7.

Table 6. Error Norms of the Least Squares and CVES Models - AMSAA Target Path

Range		Azimuth		Elevation	
(Km)	Round	LS	CVES	LS	CVES
1.2	APDS	27	200	64	221
	HEI	39	236	74	228
1.6	APDS	38	238	67	216
	HEI	35	384	67	180
Average		35	265	68	211

(Table entries are in percent.)

Table 7. Error Norms of the Least Squares and CVES Models -ATMT Target Path

Range		Azimuth		Elevation	
(Km)	Round	LS	CVES	LS	CVES
1.2	APDS	55	244	60	228
	HEI	42	306	72	170
1.6	APDS	34	315	57	202
	HEI	28	207	71	220
Average		**40**	**268**	**65**	**205**

(Table entries are in percent.)

In Tables 6 and 7, it is seen that individually and on the average, the error norms associated with the least squares model are much smaller than the existing CVES azimuth and elevation model error norms. This indicates that the least squares gunner tracking models are considerably more accurate than the CVES existing gunner models when the AMSAA and ATMT target paths are tracked. There is almost a seven-fold improvement in azimuth and about a three-fold improvement in elevation.

It is noted that the least square error norms shown in Tables 6 and 7 differ somewhat from the error norms shown in Tables 1 and 2 for similar conditions. This is because the error norms shown in Tables 1 and 2 are calculated over the second half of the output time history, whereas the error norms shown in Tables 6 and 7 are calculated over the entire output time history.

3.4 A Comparison of CVES With Actual Data

Since the newly developed least squares gunner tracking models were found to be much more accurate than the existing CVES gunner tracking models, these new models were installed in CVES. To ensure that they were compatible with CVES, the output of the simulation with the new models installed was compared to actual data.

The input to CVES with the BFVS-A3 stationary and the target moving is the target motion shown in Figures 1 and 2. It is noted that the BFVS-A3 cannot be canted within CVES. Therefore, the CVES BFVS-A3 is aligned with the inertial coordinate system, whereas in the actual test, the BFVS-A3 vehicle was canted 3.55 degrees with respect to the inertial coordinate system. Nevertheless, the same target motion was presented to the CVES gunner as the actual gunner.

Although many signals can be printed from CVES, the signals that are of primary interest are the gunner's tracking error and the system's lead angles. These are the signals that are usually of most importance when one is conducting an actual fire control test. Therefore, these signals from the CVES and the actual test were compared.

3.4.1 Tracking Error Comparison

Statistical and graphical tracking error comparisons show that the CVES is doing a reasonable job of duplicating the actual tracking errors. The AMSAA path statistical comparisons are shown in Table 8, and the ATMT path comparisons are shown in Table 9. Typical azimuth and elevation tracking error graphical comparisons associated with the AMSAA path are shown in Figures 7 and 8. Similar comparisons for the ATMT path are shown in Figures 9 and 10.

Table 8. Tracking Error Comparison, AMSAA Path

Range (Km)	Round	Test	Azimuth Avg	Azimuth SD	Elevation Avg	Elevation SD
1.2	APDS	Act	0.05	0.49	0.05	0.11
		Sim	0.03	0.55	0.00	0.09
	HEI	Act	0.05	0.51	0.03	0.11
		Sim	0.03	0.55	0.00	0.09
1.6	APDS	Act	0.03	0.49	-0.05	0.12
		Sim	0.02	0.50	0.01	0.11
	HEI	Act	0.10	0.43	0.03	0.10
		Sim	0.02	0.48	0.01	0.11

SD = standard deviation

Table 9. Tracking Error Comparison, ATMT Path

Range (Km)	Round	Test	Azimuth Avg	Azimuth SD	Elevation Avg	Elevation SD
1.2	APDS	Act	-0.01	0.41	-0.09	0.08
		Sim	0.00	0.32	0.00	0.09
	HEI	Act	0.02	0.38	0.02	0.08
		Sim	0.00	0.32	0.00	0.09
1.6	APDS	Act	0.01	0.31	0.05	0.08
		Sim	0.00	0.28	0.00	0.08
	HEI	Act	-0.01	0.29	0.07	0.08
		Sim	0.00	0.28	0.00	0.08

As Figures 7 and 8 show, the simulation reproduces the fundamental azimuth and elevation tracking error frequencies and amplitudes, and its output is in phase with the measured data. This is especially true in the azimuth plane. The comparisons are not as good in the elevation plane because the tracking error levels are much lower than in azimuth, and part of the time, they are masked by the noise. Since the simulation is deterministic rather than stochastic, it will not replicate the noise.

The statistical comparisons, which are shown in Table 8 for the AMSAA path and Table 9 for the ATMT path, show that (based on the standard deviations) the simulation tends to over-predict the magnitude of the AMSAA path azimuth tracking errors but under-predicts the magnitude of the ATMT path azimuth tracking errors. In elevation, the simulation tends to slightly under-predict the

magnitude of the AMSAA path tracking errors but just about predicts the magnitude of the ATMT path tracking errors.

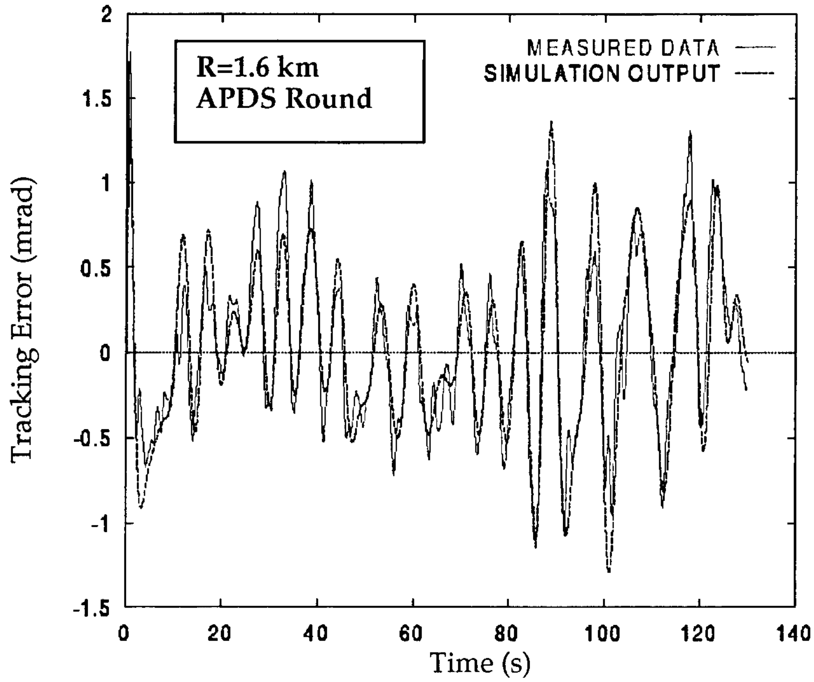

Figure 7. Comparison of Simulation and Measured Tracking Errors, AMSAA Path, Azimuth.

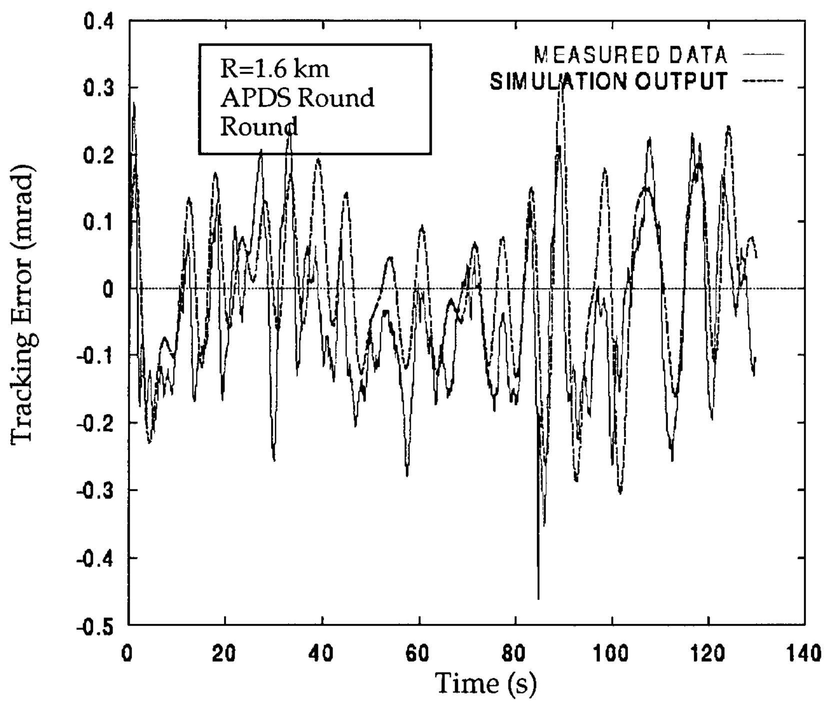

Figure 8. Comparison of Simulation and Measured Tracking Errors, AMSAA Path, Elevation.

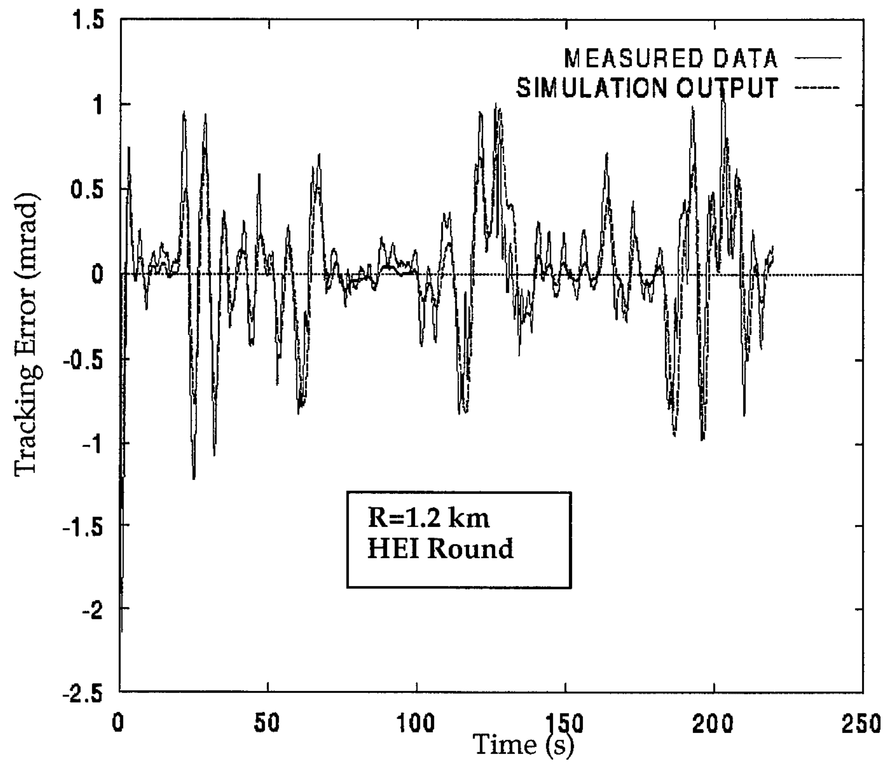

Figure 9. Comparison of Simulation and Measured Tracking Errors, ATMT Path, Azimuth.

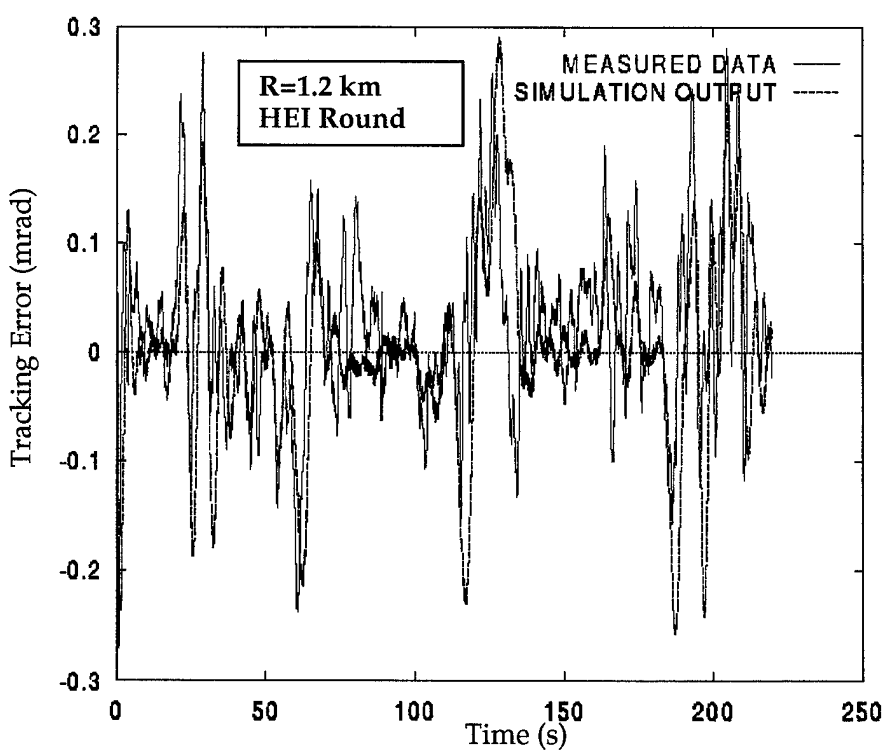

Figure 10. Comparison of Simulation and Measured Tracking Errors, ATMT Path, Elevation.

On the average, in azimuth, the simulation's AMSAA path tracking error standard deviations are about 8% larger than the actual standard deviations, and the simulation's ATMT path tracking error standard deviations are about 13% smaller. In elevation, the simulation's AMSAA path tracking error standard deviations are about 9% smaller than the actual tracking error standard deviations, and the simulation's ATMT path elevation tracking error standard deviations are about 6% larger.

For both of these paths, the elevation tracking errors are much smaller than the azimuth tracking errors because there is little target motion in the elevation plane. The target motion that is presented to the gunner in elevation is the result of the vehicle being canted a small 3.55 degrees.

The simulation's azimuth and elevation tracking error means are nearly zero for all test conditions, whereas the actual means are also small but show more variability. Averaged over all conditions tested, the actual and simulation AMSAA path azimuth tracking error means are 0.06 and 0.03 mrad, and for the ATMT path, both the actual and simulation tracking error means are zero. In elevation, the actual and simulation AMSAA path tracking error means are 0.02 and 0.01 mrad, and for the ATMT path, the actual and simulation tracking error means are 0.01 and zero mrad.

3.4.2 Lead Angle Comparisons

The statistical and graphical comparisons show that the simulation does a very good job of replicating the actual lead angles. The AMSAA path statistical comparisons are shown in Table 10, and the ATMT path comparisons are shown in Table 11. Typical AMSAA path azimuth and elevation lead angle graphical comparisons are shown in Figures 11 and 12, and similar ATMT path comparisons are shown in Figures 13 and 14.

Table 10. Lead Angle Comparison, AMSAA Path

Range			Azimuth		Elevation	
(Km)	Round	Test	Avg	SD	Avg	SD
1.2	APDS	Act	-0.27	3.95	3.63	0.15
		Sim	-0.31	3.75	3.61	0.23
	HEI	Act	-0.47	6.39	7.88	0.19
		Sim	-0.51	6.20	7.90	0.39
1.6	APDS	Act	-0.30	4.08	4.97	0.18
		Sim	-0.32	3.93	5.01	0.24
	HEI	Act	-0.54	7.40	13.17	0.25
		Sim	-0.60	7.39	13.20	0.47

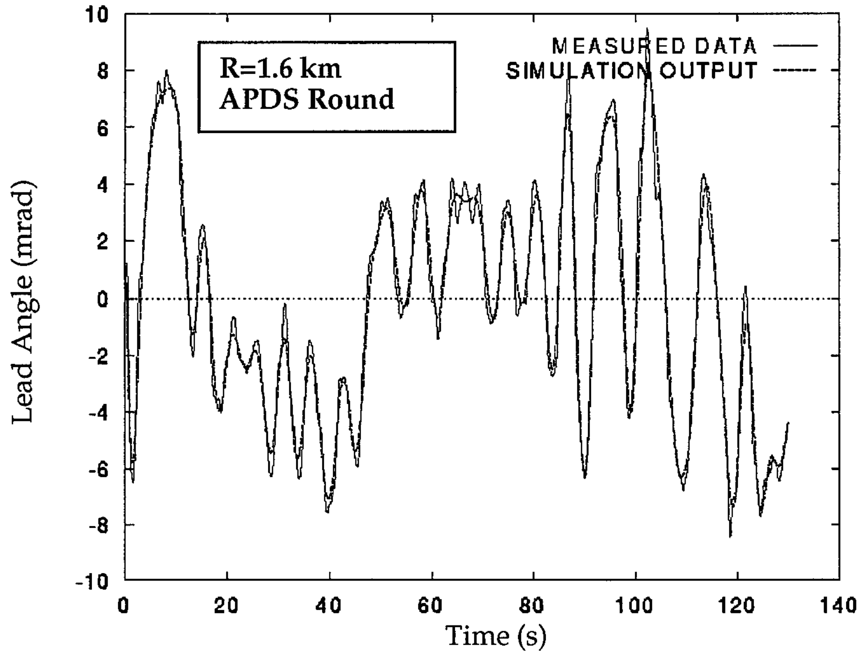

Figure 11. Comparison of Simulation and Measured Lead Angles, AMSAA Path, Azimuth.

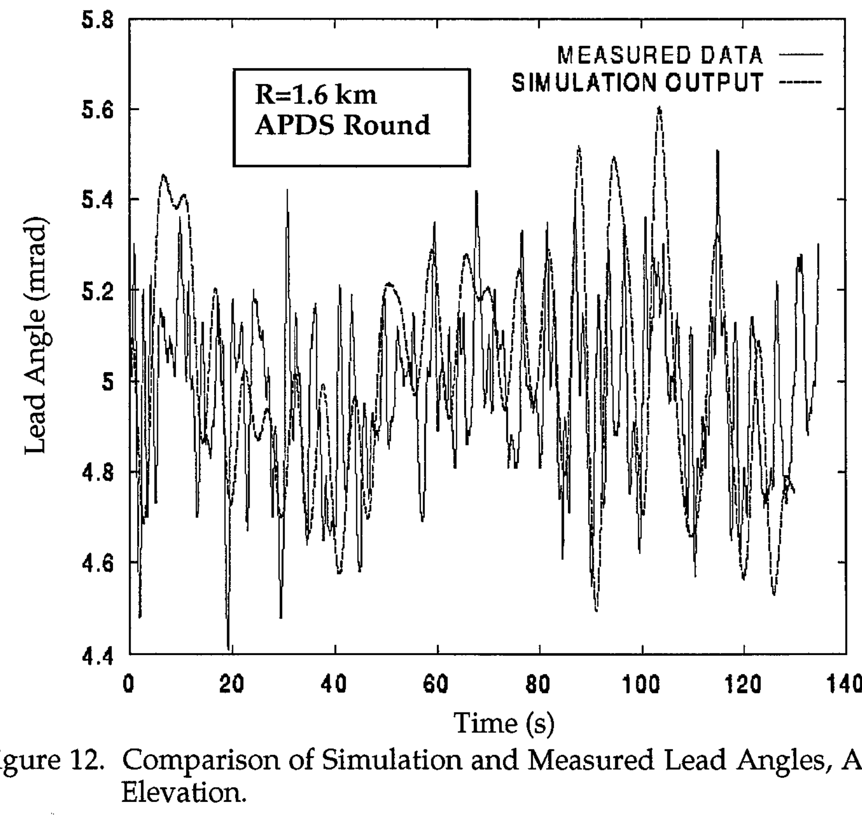

Figure 12. Comparison of Simulation and Measured Lead Angles, AMSAA Path, Elevation.

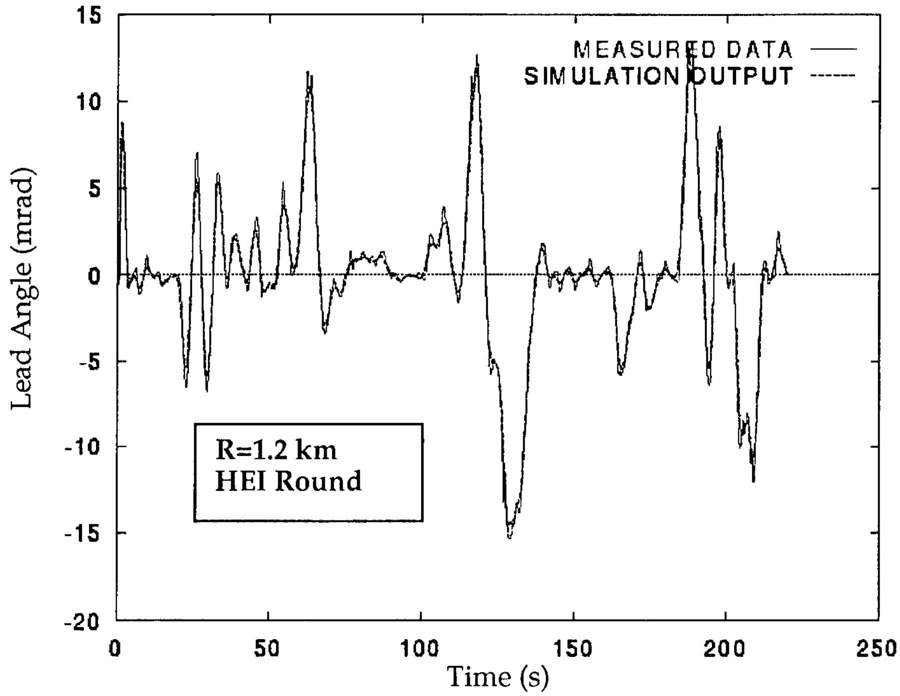

Figure 13. Comparison of Simulation and Measured Lead Angles, ATMT Path, Azimuth.

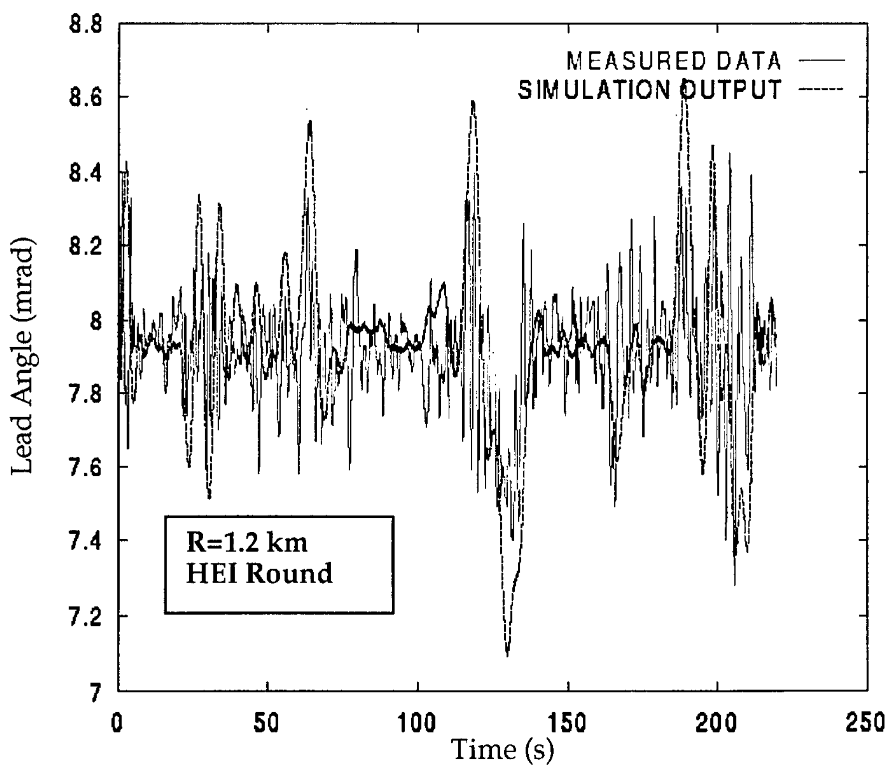

Figure 14. Comparison of Simulation and Measured Lead Angles, ATMT Path, Elevation.

From Table 10, it is seen that the simulation's AMSAA path azimuth lead angle standard deviations are (on the average) only about 3% smaller than the actual standard deviations. Both the actual and simulation azimuth lead angle means are much smaller than the standard deviations, and these means are small. Averaged over all the conditions tested, the actual AMSAA path azimuth lead angle mean is -0.40 mrad, and the simulation's mean is -0.44 mrad.

In elevation, it is seen that the AMSAA path actual and simulation lead angle means are much larger than the standard deviations and these means are nearly equal. On the average, the actual mean is 7.41 mrad, and the simulation mean is 7.43 mrad. The elevation lead angle mean is a measure of the system's super-elevation, which is required to compensate for the drop of the projectile. Therefore, the super-elevation must increase as the range to the target increases. Both the actual and simulation standard deviations are small, but the simulation's elevation standard deviation is almost 70% larger than the actual standard deviation. From Figure 12, it is seen that the elevation measured lead angle is very noisy. For the most part, the simulation seems to be following the average of the actual data.

As with the AMSAA path lead angles, it is seen from Table 11 that the simulation's ATMT path azimuth lead angle standard deviations are (on the average) also only about 3% smaller than the actual standard deviations. Both the actual and simulation azimuth lead angle means are much smaller than the standard deviations, and these means are small. Averaged over all the conditions tested, the actual ATMT path azimuth lead angle mean is -0.07 mrad, and the simulation's mean is -0.10 mrad.

Table 11. Lead Angle Comparison, ATMT Path

Range			Azimuth		Elevation	
(Km)	Round	Test	Avg	SD	Avg	SD
1.2	APDS	Act	-0.07	2.83	3.55	0.12
		Sim	-0.07	2.65	3.62	0.13
	HEI	Act	-0.06	4.58	7.91	0.16
		Sim	-0.11	4.38	7.93	0.24
1.6	APDS	Act	-0.06	2.92	5.06	0.11
		Sim	-0.07	2.77	5.02	0.14
	HEI	Act	-0.10	5.18	13.18	0.22
		Sim	-0.13	5.20	13.22	0.29

The same trends that were observed with the AMSAA path elevation lead angles are also observed with the ATMT path elevation lead angles. The ATMT path actual and simulation lead angle means are much larger than the standard

deviations, and these means are nearly equal. On the average, the actual mean is 7.43 mrad, and the simulation mean is 7.45 mrad. Both the actual and simulation standard deviations are small, but the simulation's elevation standard deviation is about 29% larger than the actual standard deviation. From Figure 14, it again is seen that in the elevation, the measured lead angle is very noisy, and for the most part, the simulation seems to be following the average of the actual data.

4. Discussion

The results in Section 3 show that the least squares azimuth gunner models are more accurate than the elevation models. This appears to be the result of the azimuth data having a larger signal-to-noise ratio (SNR) than the elevation data. The noise in both the azimuth- and elevation-averaged time history data is the result of gunner-to-gunner differences and measurement errors.

Computing the standard deviation of the tracking error and handle position signals at each time step for the four trials per test condition and then averaging these standard deviations over the entire time history gives some measure of the noise.

For the AMSAA path shown in Figures 3 and 4, the noise is 0.22 mrad for the azimuth tracking error and 1.49 degrees for the handle position. The standard deviations of the tracking error and handle position time histories shown in Figure 3 are 0.49 mrad and 9.73 degrees, respectively. This gives SNRs of 2.23 (0.49:0.22) for the azimuth tracking error and 6.53 (9.73:1.49) for the handle position. From Figure 4, the noise is 0.11 mrad for the elevation tracking error and 0.58 degree for the handle position. The standard deviations of the tracking error and handle position shown in Figure 4 are 0.12 mrad and 1.25 degrees. This gives SNRs of 1.09 (0.12:0.11) for the elevation tracking error and 2.16 (1.25:0.58) for the handle position.

Similarly for the ATMT path shown in Figures 5 and 6, the SNR is calculated to be 2.53 (0.38:0.15) for the azimuth tracking error and 6.54 (7.78:1.19) for the handle position. From Figure 6, the SNRs are calculated to be 0.89 (0.08:0.09) for the elevation tracking error and 2.18 (1.11:0.51) for the handler position.

From this analysis, it is seen that the SNR of the elevation tracking error is on the order of 1, whereas the SNR is greater than 2 for the azimuth tracking error. A similar trend is seen for the handle position data. The elevation handle position SNR is about 2.2 and the azimuth handle position SNR is about 6.5.

In Section 3, it was shown that the accuracy of the azimuth models ranged from 28.2% to 35.1%, whereas the accuracy of the elevation models ranged from 50.2% to 71.7%. Therefore, it appears as if the least squares algorithm does not have any trouble identifying models when the data exhibit large SNRs but does have some difficulty in identifying models when the data have a large noise component relative to the signal.

It was also shown in Section 3 that the transfer functions of the azimuth gunner models are very similar when each of the two target paths that were considered in this study was tracked. The frequency responses of the two azimuth models are shown in Figure 15. This result is expected since the frequency content of the tracking errors associated with each target path is similar. With this being the case, the same result should be expected in elevation. However, it is seen in Figure 16 that the gunner's elevation frequency responses differ for the two target paths. Again, this is probably the result of the low SNR of the elevation data.

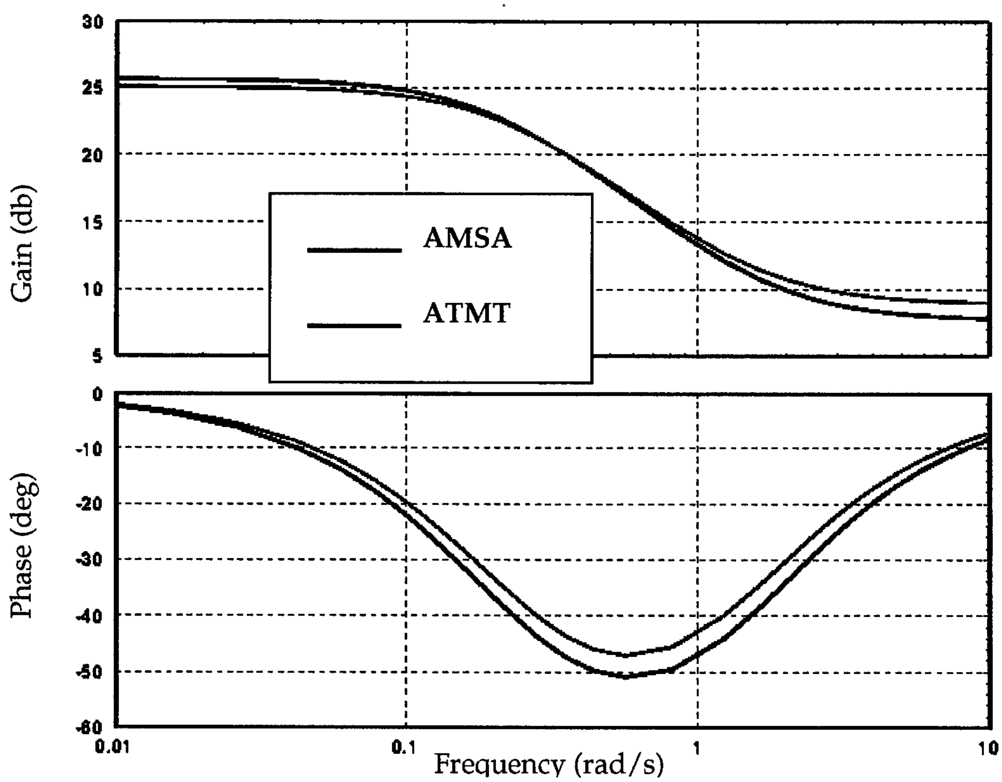

Figure 15. Least Squares Frequency Responses, Azimuth.

The results also show that the newly developed gunner models are much more accurate than the existing CVES gunner models. A comparison of the least squares and CVES azimuth model output with measured data when the ATMT target was tracked is shown in Figure 17. It is readily seen that the output of the ATMT azimuth least squares model is in much closer agreement with the measured data than is the output of the existing CVES azimuth model.

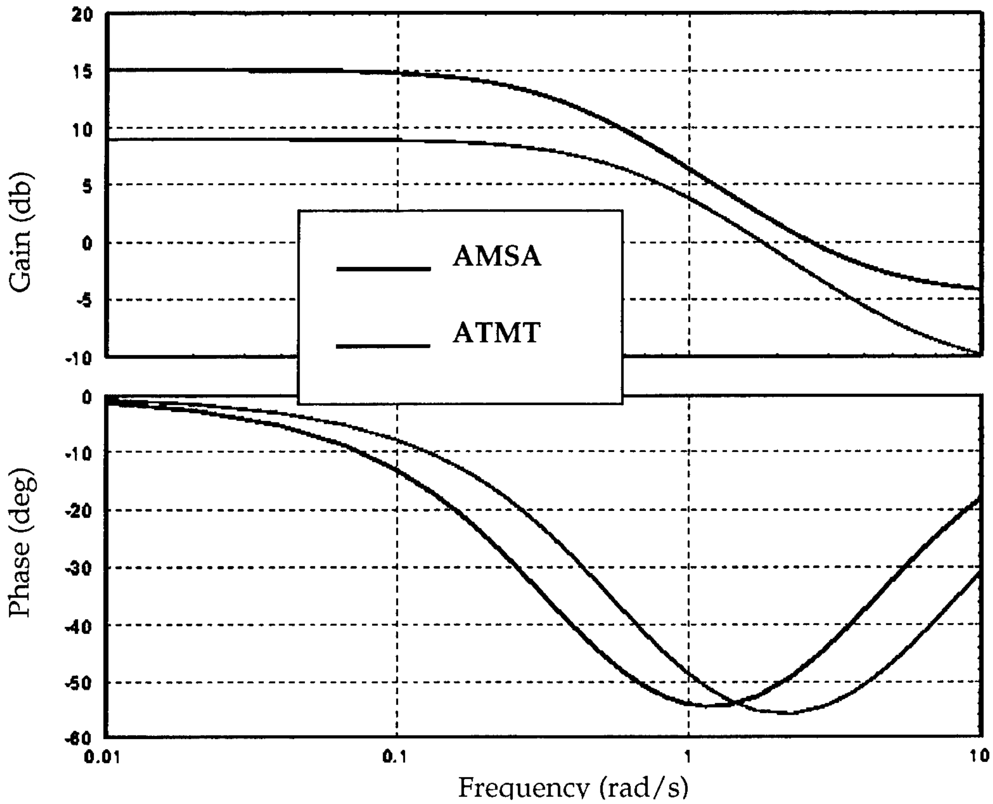

Figure 16. Least Squares Frequency Response, Elevation.

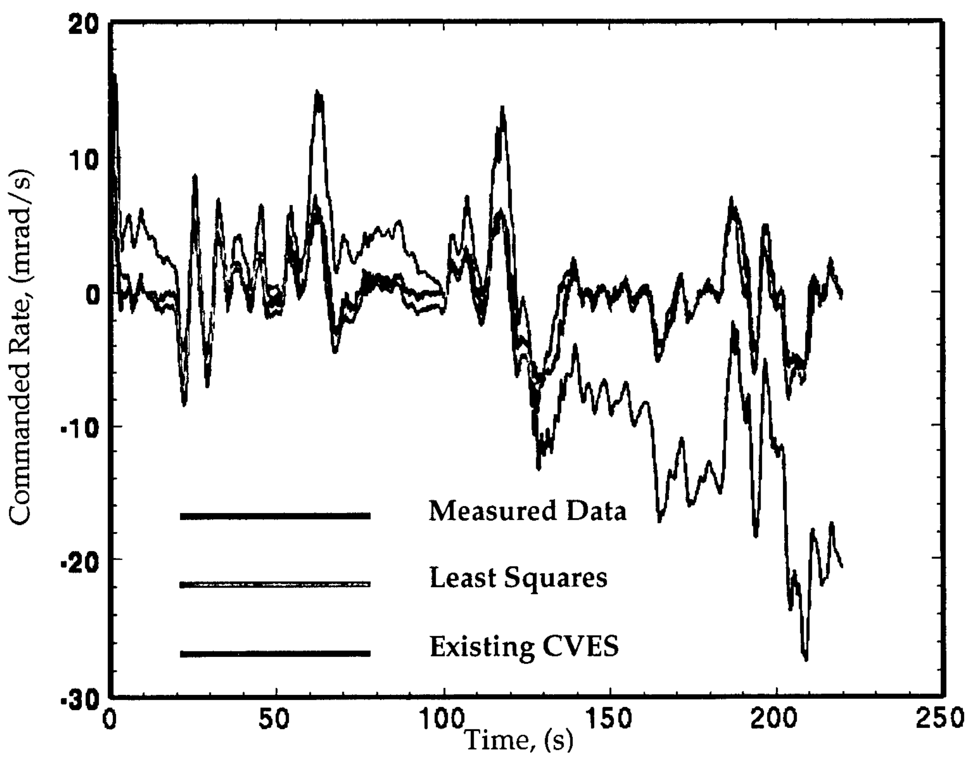

Figure 17. Comparison of the Least Squares and Existing CVES Gunner Models With Measured Data, ATMT Path, Azimuth.

A similar comparison is shown in Figure 18 for the least squares elevation model and the existing CVES model when the ATMT target was tracked. It is again readily apparent that the newly developed least squares model is in better agreement with the actual data than is the existing CVES model.

Note that in Figures 17 and 18, the ordinate is labeled "commanded rate" rather than "handle position". It was previously mentioned that the handle's output is a signal proportional to the estimated angular rate of the target. Within CVES, the gunner output is the estimated angular rate of the target rather than handle position and it is referred to as commanded rate. Thus, to make the measured data compatible with the simulation output, the measured data were multiplied by the scale factor that converts handle position to estimated target rate or commanded rate.

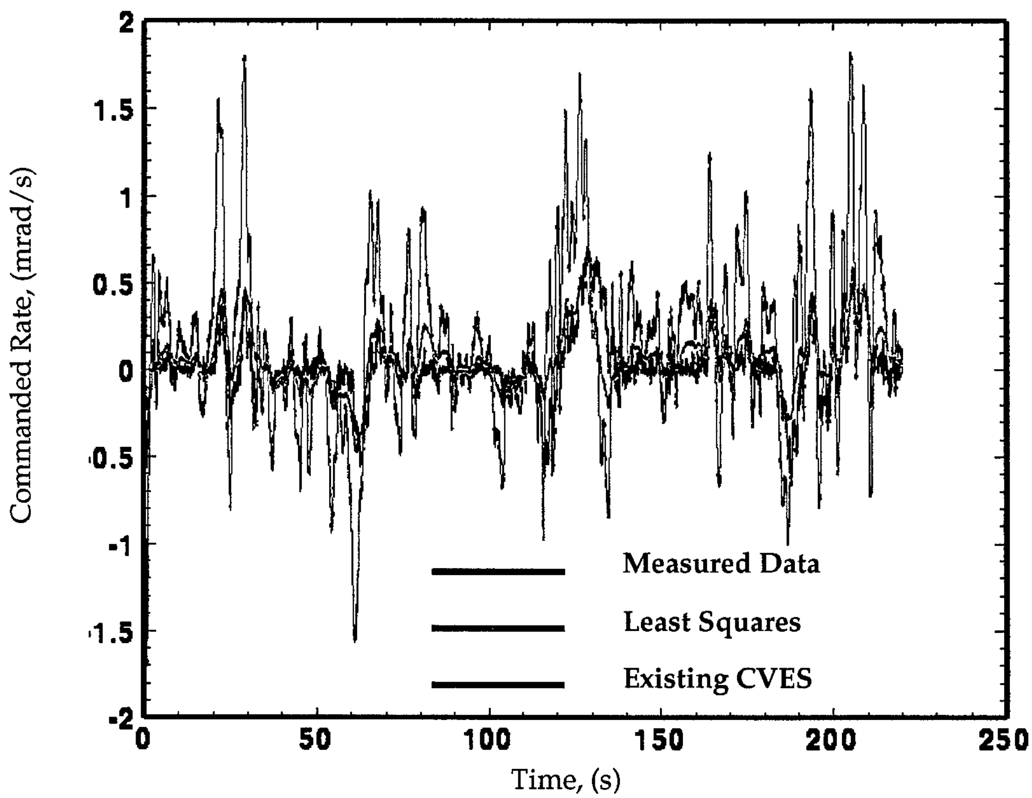

Figure 18. Comparison of the Least Squares and Existing CVES Gunner Models With Measured Data, ATMT Path, Elevation.

Other results presented in Section 3 show that the CVES tracking errors and lead angles generally agree well with actual data. There was some concern, however, with the simulation's elevation lead angles. Although small like the actual elevation lead angles, the CVES elevation lead angles were considerably larger, percentage wise. The CVES elevation lead angles were almost 70% larger when

the AMSAA target path was tracked and about 29% greater when the ATMT path was tracked.

At first, it was thought that the lower actual elevation lead angles might be the result of the vehicle not being canted the full 3.55 degrees. Discussions with the test conductor indicated that this was not the case (Scutti 2001). The vehicle cant was accurately measured. It was learned from these discussions, however, that the lead angle data supplied to ARL were referred to the inertial axis and not to the canted vehicle axis—the axes in which they were measured. As for motion in the MTS test setup, the target motion was along the inertial horizontal axis only. There was no target motion along the inertial vertical axis. (Refer to the test setup shown in Figure 19.) Therefore, given perfect tracking and a perfect fire control system, the elevation kinematic lead angle referred to the inertial coordinate system would be zero. In reality, of course, with gunner tracking errors and an imperfect fire control system, there would be some small component of lead angle along the vertical axis of the inertial coordinate system.

As mentioned previously, CVES cannot be initially canted. Therefore, in CVES, the vehicle was aligned with the inertial coordinate system. To provide the same target motion to the CVES gunner as in the actual test, target motion in CVES was provided along both the horizontal and vertical axes of the inertial coordinate system. (Refer to the simulation setup of Figure 19.) With motion along the vertical axis, an elevation lead angle will be developed. It was this lead angle that was compared to the actual data supplied to ARL. Therefore, the simulation's elevation lead angle would be larger than the actual elevation lead angle data that were supplied to ARL.

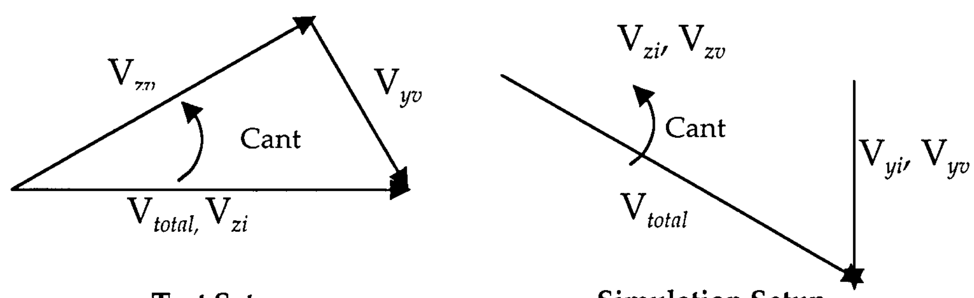

Figure 19. Comparison of the Test and Simulation Setups.

In Figure 19, V_{total} is the total target velocity, V_{yv} and V_{zv} are the components of the total velocity along the vehicle's y and z axes, and V_{yi} and V_{zi} are the components of the total velocity along the inertial y and z axes.

5. Summary

The results presented in this report show that usable gunner tracking models can be developed via measured data, along with the interactive system identification algorithms from the MATRIXx® software package. Models as high as fifteenth order were identified for each target path considered, but it was shown that the first order models were about as accurate as the higher order models. A first order model was developed for each of the target paths that were considered in this study.

It was shown that the gunner models developed with the techniques discussed in this report are more accurate than the existing gunner models that were being used in CVES. The newly developed models were about seven times more accurate than the original CVES azimuth model in predicting the gunner output and about three times more accurate than the original CVES elevation model in predicting the gunner output.

These newly developed models are simpler in their structure than the original CVES generic models. The new models are first order lag-lead networks with a steady state gain that varies as a function of range. The existing CVES azimuth gunner model consists of a time delay, a steady state gain that varies as a function of range, an integrator, a lag-lead network and a quadratic low pass filter. The existing CVES elevation gunner consists of a time delay, a gain that varies as a function of range, and a first order low pass filter.

The least squares gunner models developed for tracking the AMSAA and ATMT target paths were installed in the BFVS-A3 CVES. A comparison of the simulation's tracking errors and lead angles with actual tracking errors and lead angles shows very good agreement. There was a concern with the simulation's elevation lead angles being larger than the actual elevation lead angles, but it was shown that the difference was attributable to the way the vehicle's cant angle was handled in the simulation.

The results of this study show that the CVES with these newly developed gunner models installed is an accurate simulation for predicting the fire control performance of the BFVS-A3.

Similar techniques will be used to develop CVES versions of the interim armored vehicles and the future combat system, once data become available.

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13. ABSTRACT *(Maximum 200 words)*

During fiscal year 2000, efforts continued to develop improved gunner tracking models for the U.S. Army Research Laboratory's Combat Vehicle Engineering Simulation (CVES). By the proper selection of input, CVES can be used to determine the fire control performance of either a conceptual or specific combat vehicle. CVES has been configured to model the M1A1 combat tank and the A3 version of the Bradley fighting vehicle system (BFVS-A3). CVES contains engineering models of the fire control system, chassis, suspension, and the gunner. This effort addresses the gunner models for the BFVS-A3 CVES.

Gunner models were developed via the interactive system identification algorithms from the MATRIXx® software package, along with measured gunner tracking error and gunner handle position data. Tracking error is the gunner's input and handle position is the gunner's output.

The resulting gunner tracking models are shown to be more accurate than the existing gunner tracking models used in CVES. These new models were installed in CVES, and it was then shown that the CVES is an accurate simulation for predicting the fire control performance of the BFVS-A3.

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